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Isolated galaxies in hierarchical galaxy formation models - present-day properties and environmental histories

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ABSTRACT

In this study, we have carried out a detailed, statistical analysis of isolated model galaxies, taking advantage of publicly available hierarchical galaxy formation models. To select isolated galaxies, we employ 2D methods widely used in the observational literature, as well as a more stringent 3D isolation criterion that uses the full 3D-real space information. In qualitative agreement with observational results, isolated model galaxies have larger fractions of late-type, star forming galaxies with respect to randomly selected samples of galaxies with the same mass distribution. We also find that the samples of isolated model galaxies typically contain a fraction of less than 15 per cent of satellite galaxies, that reside at the outskirts of their parent haloes where the galaxy number density is low. Projection effects cause a contamination of 2D samples of about 18 per cent, while we estimate a typical completeness of 65 per cent. Irrespectively of the isolation criteria, roughly 45 per cent of isolated galaxies have experienced at least one merger event in the past (most of the mergers are minor, with mass ratios between 1:4 and 1:10). Our model isolated samples also include a very small (few per cent) fraction of bulge dominated galaxies ($B/T > 0.8$) whose bulges have been built mainly by minor mergers. Our study demonstrates that about 65-70 per cent of 2D isolated galaxies that are classified as isolated at $z = 0$ have indeed been completely isolated since $z = 1$ and only 7 per cent have had more than 3 neighbours within a comoving radius of 1 Mpc. Independently of the isolation criteria, the majority (about 88 per cent) of isolated model galaxies has experienced *at most* one minor merger event, when the Universe was on average half its present age. This validates the approximation that isolated galaxies have been mainly influenced by internal processes.

Key words: keywords

1 INTRODUCTION

It has been known since a long time that galaxy properties depend strongly on the environment in which they are located. E.g. it has been shown that red, early-type galaxies are preferentially residing in high-density regions while blue, late-type spirals represent the main contribution to galaxy populations in low-density environments (Oemler 1974; Dressler 1980). In recent years, the completion of large spectroscopic and photometric surveys has given new impetus to studies that are trying to assess the role of the environment in galaxy formation (e.g. Kauffmann et al. 2004; Balogh et al. 2004; Cucciati et al. 2006; Cooper et al. 2006). It remains, however, an open-issue that of understanding to what extent the properties of galaxies are determined by external physical processes that come into play only after galaxies become part of a group or of a cluster ('nurture'), or are driven by internal physical processes (e.g. star formation, AGN feedback - 'nature'). Ideally, the issue should be addressed by using a comparative approach that includes a sample of galaxies whose physical properties are largely the result of internal physical processes only. By comparing these galaxies to those residing in different environments, it should be possible to draw conclusions on the role played by nurture-induced processes. In this respect, 'isolated galaxies' have long been considered ideal candidates for a reference sub-sample of galaxies that have not experienced nurture-related processes during their lifetime.

Many observational attempts have been made in order to identify isolated galaxies by using different criteria.

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In an early study by Karachentseva (1973), a catalogue of 1050 isolated galaxies was obtained by visual inspection of photometric plates (Catalogue of Isolated Galaxies: CIG). The isolation criterion used was the following: a galaxy was classified as isolated if there was no other galaxy with similar size within 20 times its diameter. The CIG catalogue is large enough to allow a statistical comparison between isolated galaxies and galaxies from denser environments (Adams et al. 1980; Haynes & Giovanelli 1980; Sulentic 1989; Young et al. 1986; Sauty et al. 2003). In addition, the sample has a very well defined selection function, and a completeness of 80-90 per cent. Other early studies of isolated galaxies are based on only a few tens or a few hundreds galaxies (e.g. Huchra & Thuan 1977; Vettolani et al. 1986; Márquez et al. 1999, 2000; Colbert et al. 2001; Pisano et al. 2002; Varela et al. 2004). By comparing isolated spiral galaxies with spirals at different densities, Varela et al. (2004) showed that isolated spirals tend to have symmetric morphologies and to be bluer, smaller and less luminous than their non-isolated counterparts. However, this interesting result is based on a sample containing only 203 lenticular and spiral isolated galaxies. In addition, there is no accurate analysis of the completeness of the sample.

A similar study using the CIG catalogue is not easy: low-resolution and the non-linearity of the data (from the Palomar Sky Survey, POSS) represent major drawbacks for the identification of spiral galaxies. Galaxy bulges appear larger on low resolution images, and compact spirals can be misclassified easily as ellipticals or lenticular galaxies. The CIG catalog was later refined resulting into the AMIGA (**A**nalysis of the interstellar **M**edium of **I**solated **GA**laxies) sample. Work based on this sample has shown that isolated galaxies have physical properties that differ systematically from those of field galaxies. In particular, AMIGA early-type galaxies are usually fainter than late-types, and most spirals in this sample host pseudo-bulges rather than classical bulges (Verdes-Montenegro et al. 2005; Sulentic et al. 2006; Durbala et al. 2008). Moreover, the AMIGA galaxies do not show strong signatures of morphological interactions (Sulentic et al. 2006). In a recent study, Sabater et al. (2013) show that a significant fraction of (AMIGA) isolated galaxies can be identified as optical AGNs, and that there is no difference in the prevalence of AGNs between isolated galaxies and galaxies in denser environment. This indicates that major interactions are not a necessary condition for triggering optical AGNs.

Unfortunately, the term 'isolated' has been often used for samples identified using different criteria, and theoretical studies devoted to clarify the meaning and interpretation of the adopted definitions are quite scarce. It is not clear if there is a particular definition that is better than others, and how results obtained using different algorithms compare to each other. The issue is largely semantic, but results from numerical simulations can help in evaluating the performance of different selection algorithms, and support interpretation of observational results. From the theoretical point of view, a very recent study by Martig et al. (2012) analyses a set of 33 cosmological simulations of the evolution of Milky Way-like galaxies residing in low density environments. They find that the progenitors of their sample of 'isolated' galaxies span a wide range of morphological types at z=1, with the most disk-dominated galaxies having experienced an extremely quiet mass assembly. In an earlier study, Niemi et al. (2010) investigated the properties and the evolution of isolated field ellipticals using galaxy catalogues based on the Millennium Simulation. They find that roughly half of these isolated ellipticals have undergone one major merger event, and that almost all of them have experienced some merging activity during their lifetime.

A detailed investigation, however, based on different selection criteria mimicking the observational selection, has not been performed yet. In this work, we present a statistical study of isolated galaxies from a hierarchical galaxy formation model taking advantage of publicly available galaxy catalogues based on the Millennium Simulation (De Lucia & Blaizot 2007). We analyse the present-day physical properties of model isolated galaxies, as well as their environmental history. We also consider different selection criteria, comparing methods widely used in observational studies (e.g. that used to define the AMIGA sample) with a more stringent 3D isolated criterion that takes advantage of the full 3D-real space information available in simulations in order to better understand possible inaccuracies due to projection effects in observational studies.

The layout of the paper is as follows. In section 2, we briefly introduce the AMIGA sample and the isolation criteria used in Verley et al. (2007), which constitutes the basis for this study. In section 3, we shortly describe the semi-analytic model we use and how we select model isolated galaxies. Section 4 gives an overview of present-day properties of isolated galaxies both for a 2D-observational selection criterion (subsection 4.1), and for an alternative criterion based on the full 3D real-space information available from the simulation (subsection 4.2). Section 5 focuses on the 'environmental history of isolated galaxies', which we quantify by studying the parent halo mass of the progenitors of isolated galaxies, as well as their merger activity. Finally, in Section 6, we summarise and discuss our results, and give our conclusions.

2 QUANTIFICATION OF ISOLATED GALAXIES IN THE AMIGA SAMPLE

The AMIGA catalogue is a refinement of the earlier CIG catalogue of Karachentseva (1973). The AMIGA sample consists of 950 galaxies with $m_{bj} < 15.7$ and recessional velocities larger than 1500 km/s (Verdes-Montenegro et al. 2005; Verley et al. 2007). For each AMIGA galaxy, the degree of isolation was estimated considering neighbour galaxies with apparent magnitudes down to $m_{bj} = 17.5$ and with recessional velocities below $10,000$ km/s (i.e. the neighbour-sample is 'deeper', and contains more galaxies than the isolated galaxy sample, see Verley et al. 2007).

Two criteria for defining isolated galaxies were considered: the first one is based on the neighbour count, and the second one is based on the tidal strength experienced by each galaxy. For the first criterion, a local number density (Σ_{5NN}) is computed by measuring the distance to the fifth nearest neighbour:

$$\Sigma_{5NN} = \frac{k-1}{4\pi r_k^3/3}, \text{ with } k = 5. \tag{1}$$

Here, r_5 is the distance to the fifth nearest neighbour, and is

in units of arcminutes. When computing the distance from a galaxy i to its surrounding galaxies (and to select the 5th nearest neighbour), Verley et al. (2007) take into account only galaxies of similar-size:

$$1/4 \times D_i < D_t < 4 \times D_i, \quad (2)$$

where D_i is the size (i.e. the optical diameter, which is the major axis at an isophotal level of 25 mag/arcsec^2 in the B-band) of the candidate isolated galaxy, and D_t is the size of the galaxy t from the neighbour-sample. The local number density of neighbour galaxies provides a description for the environment in the vicinity of each AMIGA galaxy, but does not take into account the mass (or size) of the perturbers explicitly. Therefore, as an alternative isolation criterion, Verley et al. (2007) estimate the tidal strength affecting each AMIGA galaxy, a parameter initially proposed by Dahari (1984). In particular, they compute Q_{it}, that is the ratio between the tidal force and the binding force, which provides a measure for the tidal strength a galaxy i experiences by a neighbour galaxy t:

$$Q_{it} = \frac{F_{\rm tidal}}{F_{\rm bind}} \propto \frac{M_t \times D_i}{S_{it}^3} \times \frac{D_i^2}{M_i}, \quad (3)$$

In the above equation, S_{it} is the projected separation between the isolated galaxy i and the neighbour galaxy t, and M_i and M_t are the masses of the isolated and the neighbour galaxies, respectively. Finally, $Q = \log(\sum_t Q_{it})$ is a dimensionless estimation for the interaction strength. Also in this case, only galaxies of similar size are considered according to eq. 2. Verley et al. (2007) find that the majority of galaxies in the AMIGA sample have values oflog $\Sigma_{5NN} < 2.5$ and/or $Q < -2$. In the following analysis, we will use these limits to select isolated galaxy samples from our model galaxy catalogues.

3 THE THEORETICAL FRAMEWORK

3.1 The galaxy formation model

In this study, we take advantage of the publicly available catalogues from the galaxy formation model presented in De Lucia & Blaizot (2007). This model was applied to the dark matter merger trees extracted from the Millennium Simulation (Springel et al. 2005). The simulation assumes a WMAP1 cosmology with $\Omega_\Lambda = 0.75$, $\Omega_m = 0.25$, $\Omega_b = 0.045$, $n = 1$, $\sigma_8 = 0.9$ and, $h = 0.73$. The galaxy formation model includes prescriptions for gas cooling, re-ionization, star formation, supernova feedback, metal evolution, black hole growth, and AGN feedback. For more details on these prescriptions, we refer the reader to De Lucia & Blaizot (2007) and Croton (2006). The model has been shown to reproduce qualitatively a large variety of data, both at high redshift and in the local Universe. However, it is not without problems: the model predicts an excess of low-mass galaxies, and the predicted fraction of red galaxies is too high with respect to observational measurements. These drawbacks are not specific of this galaxy formation model, rather represent one of the major challenges even for recently published semi-analytic models (e.g. Bower et al. 2006; Monaco & Fontanot 2005; Somerville et al. 2008; Hirschmann et al. 2012), as well as for hydrodynamic simulations (Davé et al. 2011; Weinmann et al. 2012). There have been some recent attempts to solve these problems by assuming stronger SN feedback (Guo et al. 2011) and/or by changing the SF prescription (Wang et al. 2012), but none of the proposed solution is completely satisfactory and successful.

We note, however, that the drawbacks just discussed do not affect significantly the results presented in the following. We have explicitly verified that our conclusions do not vary if we use the public catalogues from the model discussed in Guo et al. (2011), applied to the Millennium II simulation. Thus, we are confident that our results, based on a comparison between isolated and non-isolated samples, are stable, even if our adopted model over-predicts in absolute terms the number of low mass galaxies.

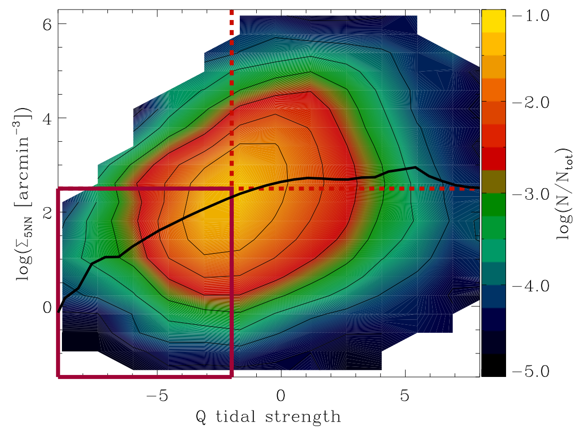

Figure 1. 2D histogram of the projected density computed using the fifth nearest neighbour Σ_{5NN}, versus the tidal strength parameter Q. The thick black line shows the median relation. Red lines indicate the cuts used for selecting isolated galaxies following the observational criteria by Verley et al. (2007). The lower left purple square illustrates the selection what we call the Iso_NN+Q sample, while the upper right region defines our high density sample.

3.2 Selecting isolated galaxies

For selecting isolated galaxies from model catalogues, we will consider two different kind of criteria:

(i) three 2D criteria, that mimic the observational selection. In particular, we will use the same criteria as in the study of Verley et al. (2007) (see description in section 2).

(ii) one 3D-criterion, where the three-dimensional information of model galaxies in the *real space* will be used. This is accessible in simulations, but generally not in observational studies.

In Table 1, we summarise the different isolated galaxy samples that we will analyse in this work.

3.2.1 2D selection

In order to select isolated galaxies following observational definitions of isolation, we mimic a real observation by

Table 1. List of the different isolation criteria and the corresponding isolated galaxy samples we will analyse in this paper.

Name	Criterion	Type	Colour code
Iso_NN	Local number density $\log \Sigma_{5NN} < 2.5$	2D-observational	green
Iso_Q	Tidal strength $Q < -2$	2D-observational	purple
Iso_NN+Q	Local number density $\log \Sigma_{5NN} < 2.5$ & Tidal strength $Q < -2$	2D-observational	orange
Iso_3D$_{\rm RS}$	No galaxy within a 1 Mpc sphere	3D-real space	cyan

putting a virtual observer in the middle of our simulation box at $z = 0$, and by converting the x, y, and z coordinates into right ascension, declination and observed redshift (recessional velocity), respectively. The latter includes the contribution from peculiar velocities. Note that we assume $z \approx 0$ throughout the box for our calculations. Following the AMIGA selection, we exclude nearby galaxies with recessional velocities below $1,500$ km/s. In addition, like Verley et al. (2007), we distinguish between a sample of candidate isolated galaxies (this is our 'parent sample', and includes all galaxies down to $m_{b,j} = 15.7$), and a sample of neighbour galaxies (the 'neighbour-sample', with an apparent magnitude cut of $m_{b,j} < 17.5$). Apparent magnitudes are calculated using the absolute magnitudes available from the catalogues, and the luminosity distances corresponding to the position of the galaxies within the box with respect to the position of the virtual observer.

We select isolated galaxies by computing Σ_{5NN} and Q as outlined in section 2. As the model used does not include prescriptions for size growth, we use the observed mass-size relation published in Auger et al. (2010) to assign a physical size to each model galaxy. This is then converted into an apparent size using the assumed geometry.

Fig. 1 shows a distribution of our model galaxies (normalised to the total number of galaxies) as a function of the tidal strength parameter Q, and of the projected local density Σ_{5NN}. The entire parent sample contains roughly 65,000 galaxies, and about one third of them are satellites. We find only a weak correlation between the tidal strength and the local density, and the majority of galaxies has a tidal strength $Q \sim -2$ and a local number density $\log \Sigma_{5NN} \sim 2$. The red lines in Fig. 1 indicate the two isolation criteria we use in the following analysis: (i) $\log \Sigma_{5NN} < 2.5$ and (ii) $Q < -2$ (consistent with the result of Verley et al. 2007). In the following, we will consider three samples of 2D-isolated galaxies satisfying either the first (i.e. 'Iso_NN' sample) or the second criterion (i.e. 'Iso_Q' sample), or both criteria (i.e. 'Iso_NN+Q' sample, see Table 1).

3.2.2 3D-real space selection

In contrast to observations, theoretical simulations provide the full three-dimensional information in the real space for all galaxies. This allows a '3D-real space' definition of isolation: we assume that a galaxy from the parent sample is isolated only when no other galaxy (from the neighbour-sample) is found within a sphere of co-moving radius of 1 Mpc[1]. To provide a fair comparison between our different isolated galaxies samples, we use the same parent sample for the 3D-real space as for the 2D-observational selection, i.e. we consider only galaxies with $m_{b,j} < 15.7$. As for the neighbour-sample, we consider only galaxies with masses larger than one order of magnitude below the mass of the isolated galaxy, i.e. $\log(M_{\rm iso}/M_\odot) - 1 < \log(M_{\rm neighbour}/M_\odot)$. This way, we put a homogeneous upper limit to the tidal strength exerted by the neighbours on each isolated galaxy, irrespectively of its mass.

4 PRESENT-DAY GALAXY PROPERTIES

In this section, we focus on basic properties of present-day isolated model galaxies selected by using different criteria. For each sample of isolated galaxies, we construct a corresponding *mass-matched random sample* i.e. a random galaxy sample with the same magnitude cut, same total number of galaxies, and the same stellar mass distribution of the corresponding isolated sample. This allows us to take out the strong dependency of galaxy properties on stellar mass, and perform an unbiased comparison between isolated galaxies properties and 'average' galaxy properties.

4.1 2D isolation criteria

4.1.1 Stellar masses

The top panel of Fig. 2 shows the stellar mass distributions for the three 2D selected isolated galaxy samples, as indicated in the legend. For comparison, the black line shows the stellar mass distribution of high-density galaxies residing in the top right quadrant of Fig. 1 (i.e. those corresponding to $\log \Sigma_{5NN} > 2.5$ and $Q > -2$). In qualitative agreement with observational findings, isolated galaxies tend to have lower stellar masses than galaxies residing in dense regions. Comparing the different isolated samples among each other shows that the stellar mass distributions of isolated galaxies from the Iso_Q and the Iso_NN+Q samples are very close to each other at the high mass end, and only slightly different at the low mass end. The latter difference is likely due to galaxies that are surrounded by a large number of lower/similar mass ones, failing the Iso_NN criterion but passing the Iso_Q one. Compared to the Iso_NN sample, galaxies from the Iso_Q and from the Iso_NN+Q samples tend to have significantly lower stellar masses ($< 10^{11.5} M_\odot$). In other words, when selecting isolated galaxies using the Q-parameter, one loses a relatively large number of massive galaxies that have a low

[1] Note that 1 Mpc is roughly the distance to the first nearest neighbour when applying both 2D-observational selection criteria. In addition, this selection results in a similar number of galaxies as in the Iso_NN+Q sample.

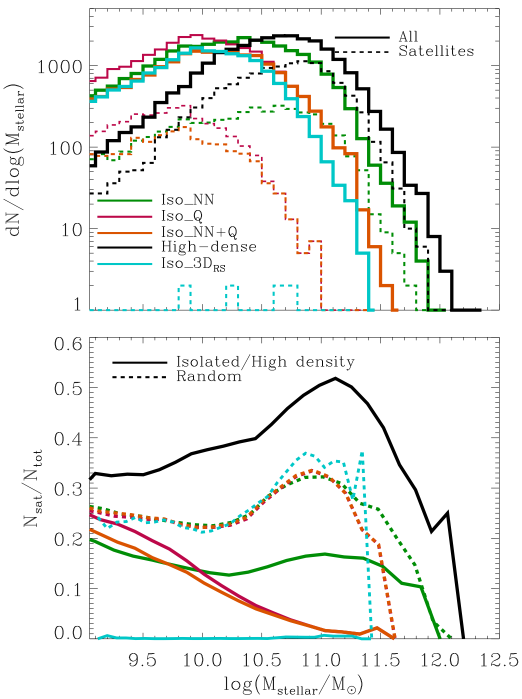

Figure 2. Upper panel: present-day stellar mass distributions for 2D observationally and 3D-real space selected isolated galaxies (Iso_NN: green, Iso_Q: purple, Iso_NN+Q: orange, Iso_3D$_{\rm RS}$: cyan). For comparison, the black line illustrates the corresponding distribution for 'high-density' galaxies. Dashed lines indicate the corresponding distributions for the satellite galaxies in each sample. Bottom panel: Fraction of satellite galaxies as a function of stellar mass for the different isolated samples, and the high-density sample considered in the upper panel.

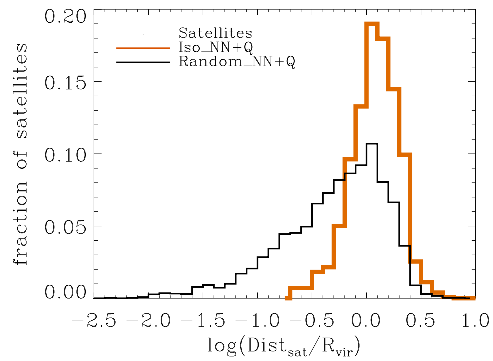

Figure 3. Fractions of satellites versus the distances to their parent halo centre, normalised to the virial radius. The thick orange line corresponds to galaxies selected from the Iso_NN+Q sample, while the thin black line illustrates the corresponding random sample.

numbers of neighbours, but high Q values. These galaxies are preferentially living as pairs, triplets or dense small systems: i.e. massive galaxies with several massive neighbours close enough to 'disturb' them significantly. This shows the importance of adding also the Q-cut (i.e. considering also the mass of the neighbouring galaxies) to avoid 'contamination' of isolated samples from these systems.

4.1.2 Isolated satellite galaxies

The bottom panel of Fig. 2 shows the fraction of satellite galaxies for the different isolated galaxy samples. We find, independently of the isolation criterion used, a clear prevalence of central galaxies for the isolated galaxy population. Satellite galaxies constitute only a minor fraction of the isolated galaxies (less than 15 per cent). For comparison, the black line shows the satellites fraction for the high-density galaxy sample (top right quadrant in Fig. 1), which is much larger than the corresponding fraction for all isolated galaxy samples. However, when comparing the 2D isolated samples with the corresponding mass-matched random samples (dashed lines of the same colour), 'typical' galaxies of the same stellar mass have a significantly larger fraction of satellites (~ 25 per cent) peaking at stellar masses about $10^{11} M_{\odot}$). While for the Iso_Q and the Iso_NN+Q samples, the satellite fraction is decreasing with increasing stellar mass, for the Iso_NN sample the satellite fraction is roughly constant as a function of stellar mass and equal to about 15 per cent. This confirms that the high mass tail rejected by the Iso_Q criterion is composed by relatively massive galaxies located in small, isolated systems. In these systems such galaxies would be the satellites.

The presence of satellite galaxies in the isolated samples might appear counter-intuitive, and certainly in contradiction with the term 'isolated'. Indeed, by definition, these galaxies have experienced nurture-related physical processes at least for some fraction of their lifetime. It is, therefore, interesting to understand why and under which conditions, a satellite galaxy ends up being selected as a candidate isolated galaxy. Fig. 3 shows the distribution of the radial distances of satellites to their parent halo centre for the Iso_NN+Q sample, and for the corresponding mass-matched random satellite sample. The radial distances are normalised to the virial radius of the parent halo. We find that isolated satellites are most likely located at the outskirts or even outside of the virial radii of the parent halos: $0.5R_{\rm vir} < {\rm Dist}_{\rm sat} < 3R_{\rm vir}$. In contrast, randomly selected satellites tend to live closer to the parent halo centre and thus, their distances span a broader range between $0.01R_{\rm vir} < {\rm Dist}_{\rm sat} < 3R_{\rm vir}$. In summary, isolated samples selected using the criteria illustrated in the section 3.2.1 contain a fraction of satellite galaxies ranging between 10 and 15 per cent, with the fraction being smaller when the Q parameter is employed for the selection. The satellites selected as isolated are generally those residing at the outskirts of haloes, where the local galaxy density is lower. Surprisingly, we also find that roughly half (55 per cent) of the satellites classified as isolated, have been satellites for more than 2 Gyr. Therefore, these galaxies have been exposed to environmental physical processes, and their physical properties have not been determined by internal physical processes only. We find that these galaxies reside preferentially in massive host halos ($> 10^{13} M_{\odot}$), and have been accreted with low average mass ratio ($M_{\rm subhalo}/M_{\rm hosthalo} \sim 0.02$), so that their survival time as satellites are relatively long.

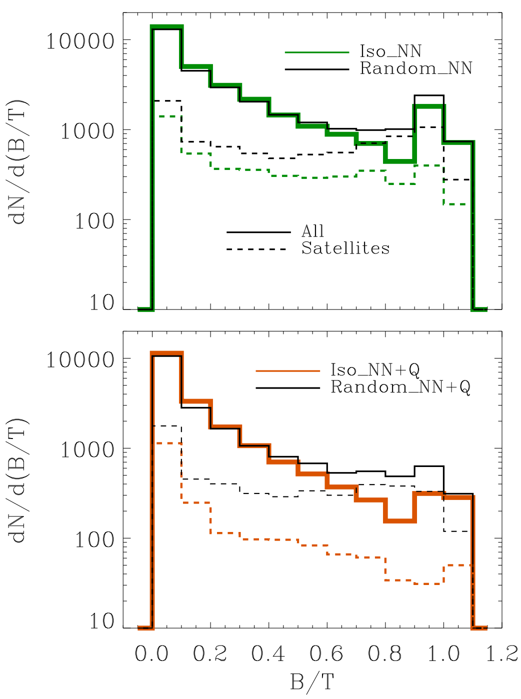

Figure 4. Histograms of the bulge-to-total ratios for observationally selected isolated galaxies, and for the corresponding mass-matched random samples, as indicated in the legend. Dashed lines show the corresponding distributions for the satellite galaxies. Different panels illustrate the different criteria (see legend).

4.1.3 Morphology

In Fig. 4, we show the distributions of the stellar mass bulge-to-total ratios for two different 2D-isolated galaxy samples (top panel: Iso_NN; bottom panel: Iso_NN+Q). We do not discuss here the Iso_Q sample separately, as results do not differ significantly from those shown for the Iso_NN+Q sample. The black lines correspond to the respective mass-matched random sample, and dashed lines illustrate the contribution from satellites. We find that all isolated and random samples are clearly dominated by late-type galaxies, but with a varying fraction of early-type (bulge-dominated) galaxies. Comparing the two isolated samples, the Iso_NN sample contains roughly ~ 20 per cent of bulge-dominated (B/T ratio > 0.8) galaxies, while the Iso_NN+Q sample includes only about 4 per cent of these galaxies. This can be explained in part by the stellar mass distributions: compared to the Iso_NN sample, the Iso_NN+Q galaxies are shifted towards lower stellar masses, which have generally a smaller bulge component. By comparing isolated samples to the corresponding mass-matched random ones, we find that the latter include a larger fraction of bulge-dominated systems.

It is interesting to study the sub-sample of isolated ellipticals (with B/T ratio > 0.8) in more detail. We find that it contains only few low-mass galaxies, i.e. isolated ellipticals tend to reside among the most massive in each sample considered, with a peak in their stellar mass distributions between $10^{10.5}$ and $10^{11} M_{\odot}$. In the galaxy formation model considered in our study, bulges can grow through merger events and through secular evolution processes like disk instabilities. Distinguishing the contribution from these two channels, we find that bulges of isolated early-type galaxies (Iso_NN+Q) have been built either by disk instabilities only or by merger events only, but not through a combination of these processes. The vast majority of these bulges have been formed via merger events with a mass ratio between 1:1 and 1:10. In particular, for the Iso_NN+Q early-types, we find that 96% of the bulges have formed via major and minor mergers. In addition, we find that roughly two-thirds of the merger-formed bulges of isolated ellipticals have been assembled via minor mergers (mass ratio between 1:4 and 1:10), just like for the respective mass-matched random sample.

The presence of bulge-dominated galaxies in the isolated samples, and the finding that most of these bulges are formed through merger events, suggest that at least a fraction of the present-day isolated galaxies (the majority of those with a high bulge-to-total ratio) have not always been isolated during their lifetime, and must have been interacting with neighbouring galaxies. This result will be discussed in more detail in section 5.3. We note that our findings are in agreement with the study by Niemi et al. (2010). They used galaxy catalogues from the same model adopted in this study, and found that almost all ($\sim$98 per cent) of the isolated ellipticals experience some merger activity during their evolution. However, while about one third of *our* isolated early-type galaxies have experienced at least one major merger event during their lifetime, Niemi et al. (2010) find a larger fraction of isolated ellipticals ($\sim$46 per cent) having experienced at least one major merger. The discrepancy is likely caused by the different magnitude cuts and isolation criteria used.

4.1.4 Star formation

Fig. 5 shows the distribution of the Specific Star Formation Rates (sSFR $=$ SFR$/M_{\rm stellar}$) for two different 2D-isolated galaxy samples (top panel: Iso_NN; bottom panel: Iso_NN+Q). The black lines correspond to the respective mass-matched random sample, while dashed lines illustrate the contribution from satellite galaxies. We find that all isolated and mass-matched random samples are dominated by star forming galaxies (with $\log {\rm sSFR} > -11$), which is a direct consequence of the fact that isolated galaxies (in all samples) are dominated by galaxies of low stellar masses. In the Iso_NN sample, roughly 70 per cent of the galaxies are star-forming, and the distribution of isolated galaxies is very similar to that of the corresponding mass-matched random sample. In contrast, in the Iso_NN+Q sample, a larger fraction of galaxies are star-forming ($\sim 85\%$) than in the corresponding mass-matched random sample ($\sim 68\%$). Independently of the galaxy sample, satellites provide a relatively larger contribution to the quiescent fraction of isolated galaxies than centrals. However, this is basically by definition. Indeed, the galaxy formation model used in this study adopts an instantaneous strangulation of the hot gas reservoir after accretion of galaxies onto larger systems. This switches off cooling on satellite galaxies, and quenches their star formation on very short time-scales. It is known that this assumption produces an excess of faint and passive satellites in galaxy formation models. As a consequence, different studies (e.g. Weinmann et al. 2010; Wetzel et al.

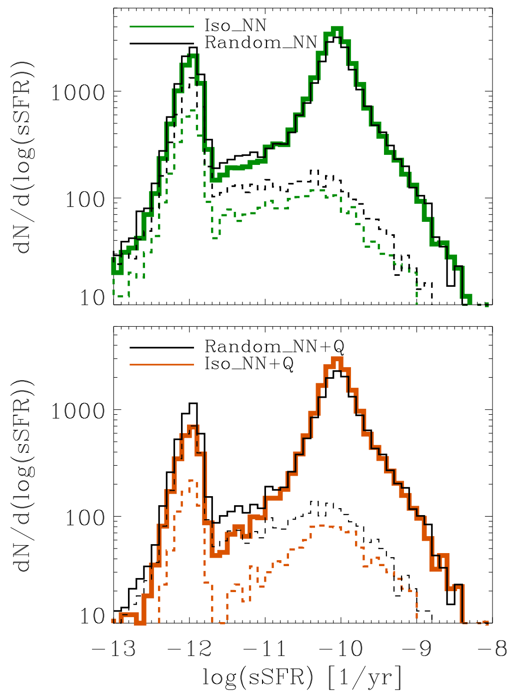

Figure 5. Histograms of the specific star formation rates for 2D-observationally selected isolated galaxies, and for the corresponding mass-matched random samples. Dashed lines show the corresponding distributions for satellite galaxies. Different panels illustrate the different selection criteria, as indicated in the legend.

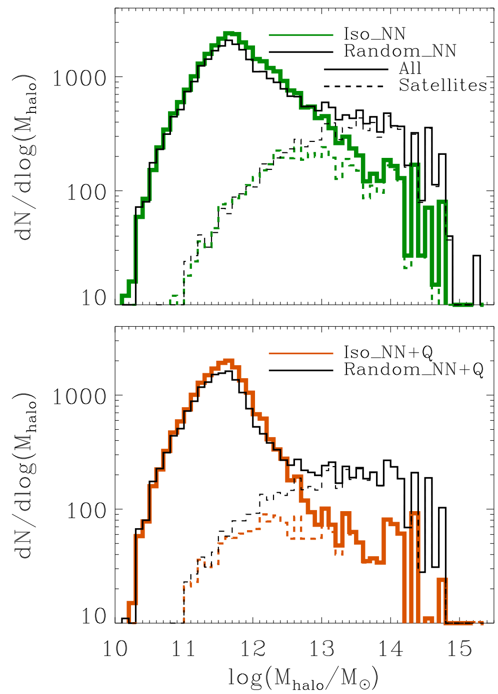

Figure 6. Distributions of the parent halo masses for 2D-observationally selected isolated galaxies, and for the corresponding mass-matched random samples. Dashed lines show the corresponding distributions for the subsamples of satellite galaxies. Different panels illustrate the different selection criteria, as indicated in the legend.

2012; De Lucia et al. 2012 and references therein) suggest much longer quenching time-scales, with typical values of $5-7$ Gyr.

4.1.5 Parent halo masses

Fig. 6 shows the distributions of parent halo masses for two isolated galaxy samples (top panel: Iso_NN; bottom panel: Iso_NN+Q), and for the corresponding mass-matched random samples. The majority of both random and isolated galaxies reside in parent halos with masses below $10^{13} M_{\odot}$, and these galaxies are most likely centrals. In contrast, the massive ends of the distributions (above $10^{13} M_{\odot}$) are completely dominated by satellite galaxies. For the Iso_NN sample, we obtain a slightly larger fraction of isolated galaxies living in halos with masses above $10^{12} M_{\odot}$ than for the Iso_NN+Q sample. This is just a reflection of the larger amount of (massive) satellite galaxies in the Iso_NN sample (see bottom panel in Fig. 2), which are know to preferentially reside in massive halos.

Comparing the isolated to their mass-matched random samples, we find that the latter exhibit a significantly larger amount of galaxies residing in halos above $10^{13} M_{\odot}$. Again, this is a direct consequence of the larger fraction of satellites in the mass-matched random samples than in the isolated ones. At the low mass end (below halo masses of $\sim 10^{13} M_{\odot}$) the halo mass distributions of the isolated and random samples are very close to each other, independently of the chosen isolation criterion. Vice versa, the difference at the high mass end between the mass-matched random and isolated samples is stronger for the Iso_NN+Q sample. Our results imply that the probability for an isolated galaxy to reside in a massive halo is significantly reduced compared to a typical, non-isolated galaxy of the same mass (because the isolated galaxy has - by definition - a lower probability of being a satellite galaxy).

4.1.6 Black holes in isolated galaxies

In our galaxy formation model, the formation of bulges through mergers proceeds in parallel with the formation of black holes. As seen in section 4.1.3, a non negligible fraction of isolated galaxies do also host a bulge, though this is generally not the dominant component. Hence, it is interesting to analyse the relation between black hole and bulge masses of isolated galaxies in order to investigate whether it deviates systematically from that measured for the global bulge-dominated galaxy population. For the Iso_NN+Q sample and the corresponding mass-matched random one, we find that roughly 75 per cent of the galaxies host black holes with masses above $10^6 M_{\odot}$, but they do not contain any black holes with masses above $10^9 M_{\odot}$ (see upper panel of Fig. 7, orange and black solid lines). The black holes of the Iso_NN+Q sample are slightly less massive than the ones of the corresponding mass-matched random sample. Thus, the fact that isolated galaxies do not host the most massive

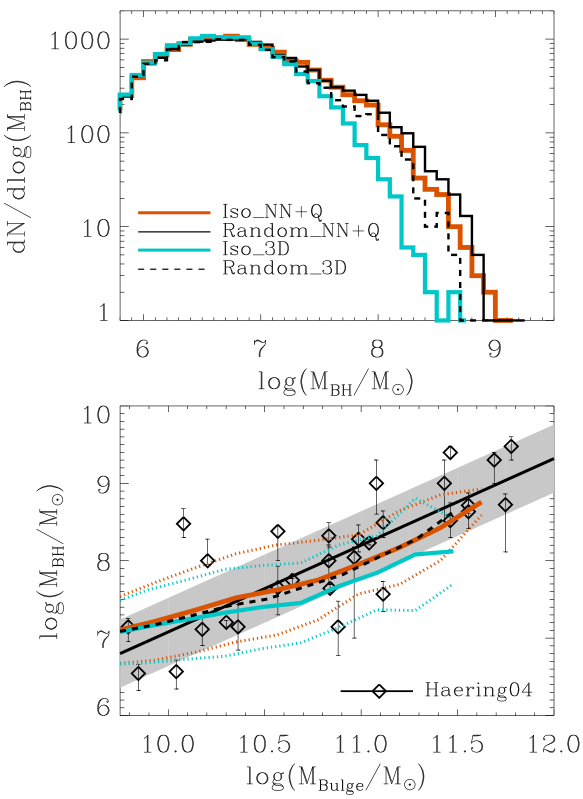

Figure 7. Top panel: Distributions of the black hole masses for the Iso_NN+Q and the Iso_3D$_{\rm RS}$ isolated galaxies, and for the corresponding random samples. Bottom panel: Black hole-bulge mass relation for the Iso_NN+Q, the Iso_3D$_{\rm RS}$, and the Random_3D$_{\rm RS}$ samples (the relation corresponding to the Random_NN+Q sample is identical to that of the Iso_NN+Q one). Dotted lines indicate the 1-σ scatter. Model predictions are compared with the observed relation from Häring & Rix (2004) (black symbols). The black solid line with the grey shaded area shows a fit to the observational data.

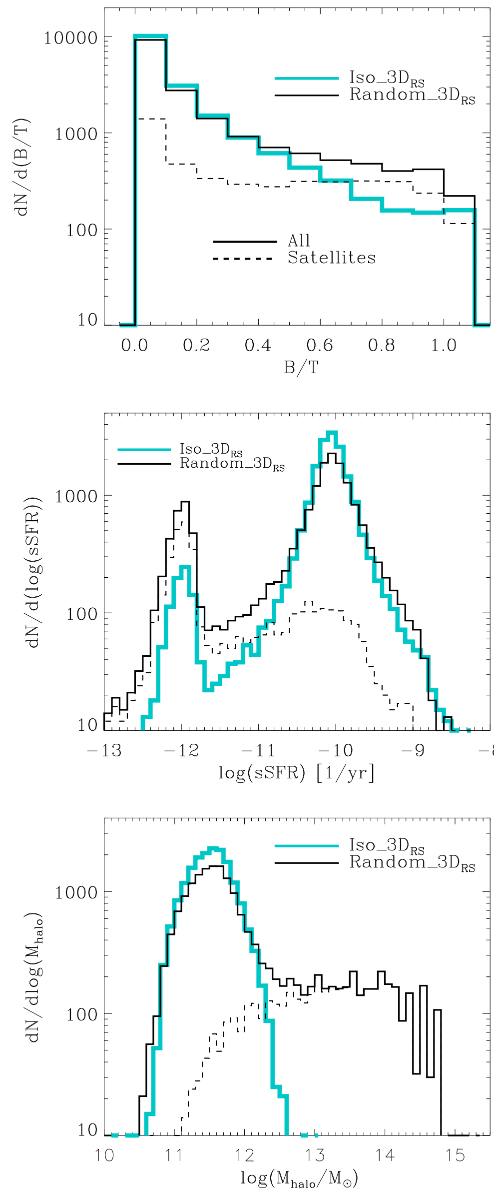

Figure 8. Histograms of the bulge-to-total ratio (top panel), of the specific SFR (middle panel) and of the parent halo mass (bottom panel), using the 3D-real space selected isolated galaxy sample (cyan line) and its mass-matched random sample (black line). Dashed lines illustrate satellite galaxies.

black holes in the Universe is not just due to the fact that their stellar mass distribution is skewed towards low values.

The lower panel of Fig. 7 shows the black hole-bulge mass relation for isolated galaxies in the Iso_NN+Q as an orange line. We do not explicitly show the relation for the mass-matched random sample as it is nearly identical to the one obtained for the isolated sample. When comparing this relation to the observed one (Häring & Rix 2004) for the overall galaxy population (illustrated by the symbols and the black line with the grey shaded area), we find that black holes with mass $> 10^{10.2} M_{\odot}$ in isolated galaxies tend to be slightly under-massive at a given bulge mass. This is, however, true also for the randomly selected sample: in other words, the model we are using predicts a black hole-bulge mass relation which is slightly shallower than in the observations (see e.g. Marulli et al. 2008).

In summary, the isolation criteria tends to exclude the most massive black holes, but does not alter significantly the predicted black hole-bulge mass relation with respect to that obtained from a random mass matched sample.

4.2 3D-real space isolation criterion

We now turn to the full 3-dimensional real space information from our theoretical models, and focus on the 3D isolation criterion described in section 3.2.2. The cyan lines in Fig. 2 show the stellar mass distribution (top panel) and the fraction of satellite galaxies (bottom panel) for the isolated sample selected using the full 3D information. In this case, isolated galaxies have stellar masses lower than $3 \times 10^{11} M_{\odot}$, and their mass distribution shape is only slightly different than that of Iso_NN+Q. In addition, the Iso_3D$_{\rm RS}$ sample contains only a few satellite galaxies: the 3D isolation criterion used is quite efficient in removing the residual satellite

galaxies entering the Iso_NN+Q sample, which - as we discussed in section 4.1.2 - inhabit mostly the outskirts of their parent haloes. We note that given the scale and mass limits adopted, this happens almost by construction: excluding galaxies with neighbours with stellar mass down to one order of magnitude below the candidate isolated galaxy, and within 1 Mpc from it, excludes most of the satellite galaxies.

Fig. 8 shows the distribution of the bulge-to-total ratios (top panel) for the Iso_3D$_{\rm RS}$, and the corresponding mass-matched random sample. Dashed lines illustrate the contribution from satellite galaxies. Regarding the morphology, we find that the Iso_3D$_{\rm RS}$ galaxies tend to be clearly less bulge-dominated than the corresponding mass-matched randomly selected galaxies. This is mainly due to the negligible amount of isolated satellite galaxies compared to the random sample, which tend to be bulge-dominated (see the black dashed line). The same qualitative trend, though less pronounced, was found for the Iso_NN+Q sample (see Fig. 4). As for the Iso_NN+Q sample, also the Iso_3D$_{\rm RS}$ sample contains a small (about 2.7 per cent) fraction of isolated early-types ($B/T > 0.8$), which tend to be more massive than a 'typical' isolated galaxy. For 3D selected isolated early-types, we find that about 86 per cent of the bulges have been formed via major and minor mergers only, a slightly smaller fraction than for the Iso_NN+Q sample. Again, for these merger-formed isolated early-types, minor mergers are with two thirds the dominating contribution in the build-up of the bulge component. This means that also a small fraction of Iso_3D$_{\rm RS}$ galaxies (all the isolated early-types) have not been isolated for their entire life, but have been subject to interactions with other galaxies.

The middle panel of Fig. 8 shows the distribution of specific SFRs for the Iso_3D$_{\rm RS}$ and the corresponding mass-matched random sample. We find that 3D$_{\rm RS}$ isolated galaxies include a high percentage of star-forming galaxies (~ 94 per cent), which is slightly higher than the one of the Iso_NN+Q sample, and significantly larger than the one of the corresponding mass-matched random galaxy sample (~ 77 per cent). A large part of the difference between the Iso_3D$_{\rm RS}$ sample and the mass-matched random sample is due to the fact that the isolated sample includes only an extremely low fraction of satellite galaxies, which tend to be passive in our galaxy formation model. We find that roughly all of the passive isolated galaxies in the Iso_3D$_{\rm RS}$ sample are central galaxies with relatively high stellar masses ($\sim 10^{10.5-11.5} M_{\odot}$), likely quenched by AGN feedback.

Turning now to the parent halo mass distribution (bottom panel of Fig. 8), we find that 3D$_{\rm RS}$ isolated galaxies are all living in haloes of mass below $10^{13} M_{\odot}$. In contrast, 'typical' galaxies at various densities (the mass-matched random sample) have a non-negligible probability to live in parent halos with masses above $10^{13} M_{\odot}$, where the main contribution comes from satellite galaxies missing in the Iso_3D$_{\rm RS}$ sample. When comparing the 2D selected isolated galaxies (Iso_NN+Q) with the Iso_3D$_{\rm RS}$ ones, we find that the amount of galaxies living in massive halos is significantly larger in the Iso_NN+Q sample. Again, as explained earlier, this is due to the satellites living at the outskirts of massive halos in the Iso_NN+Q sample.

Regarding black holes in 3D$_{\rm RS}$ isolated galaxies and in the corresponding mass-matched random sample, Fig. 7 shows the black hole mass distributions (cyan and black dashed lines in the upper panel). 3D$_{\rm RS}$ isolated black holes have masses that do not exceed $10^{8.5} M_{\odot}$, and are typically significantly less massive than the black holes in the Iso_NN+Q galaxy sample and in the Random_3D sample. Furthermore, considering the black hole-bulge mass relation for the Iso_3D$_{\rm RS}$ and Random_3D$_{\rm RS}$ galaxy samples (see cyan and black dashed lines in the bottom panel of Fig. 7), we find that both samples produce slightly under-massive black holes at a given bulge mass compared to the observed relation. However, the Iso_3D$_{\rm RS}$ black holes are even more under-massive than the ones of typical galaxies with the same stellar mass, and also than Iso_NN+Q black holes (orange line). So in the case of the Iso_3D$_{\rm RS}$, the isolation criterion used affects both the number density of the most massive black holes, and the median black hole-bulge mass relation.

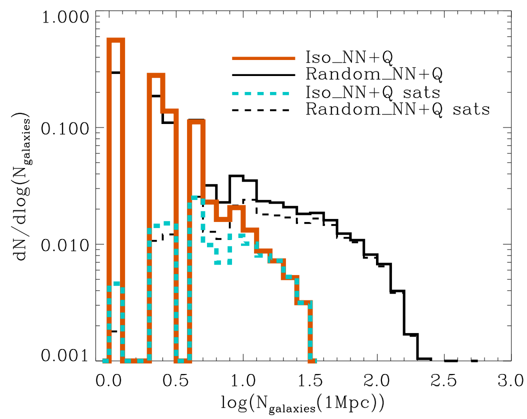

Figure 9. Histogram showing the number of galaxies found within a 1 Mpc sphere (including the central one) for the Iso_NN+Q (orange), and for the corresponding mass-matched random galaxy sample (black). Satellites are indicated by cyan and black dashed lines, respectively.

4.3 3D-isolation degree of 2D selected isolated galaxies

The differences between 2D and 3D$_{\rm RS}$ selected isolated galaxies are largely due to projection effects affecting the 2D sample. Albeit our 3D criterion is also somewhat arbitrary (one can use a different radius and/or different mass limits), it is interesting to quantify which fraction of the 2D selected isolated galaxies (those in the Iso_NN+Q sample) would also be isolated using the 3D-real space information. Fig. 9 shows the distribution of the number of galaxies within a 1 Mpc sphere for the Iso_NN+Q galaxies, and for the corresponding mass-matched random sample. As usual, satellites are indicated by dashed lines. We find that about 56 per cent of 2D isolated galaxies, and about 28 per cent of the corresponding random galaxies are isolated when considering our 3D criterion (no neighbour galaxy within the 1 Mpc sphere with a mass larger than one order of magnitude below the mass of the isolated galaxy). However, there is a large percentage (about 82 per cent) of the 2D isolated galaxies, which have less than 3 neighbours within the 1 Mpc sphere. The main contribution to 2D isolated galaxies (as well as to

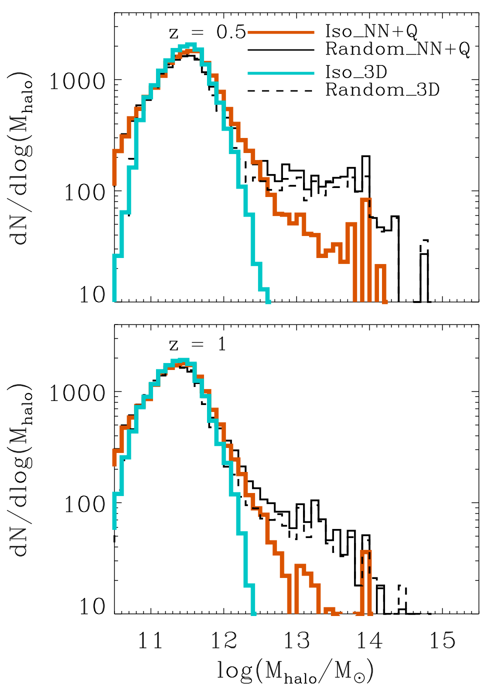

Figure 10. Distributions of parent halo masses for progenitors of the Iso_NN+Q (orange) and the Iso_3D$_{\rm RS}$ (cyan) samples, and of their mass-matched random samples (black). Different panels refer to different redshifts (top: z=0.5, bottom: z=1).

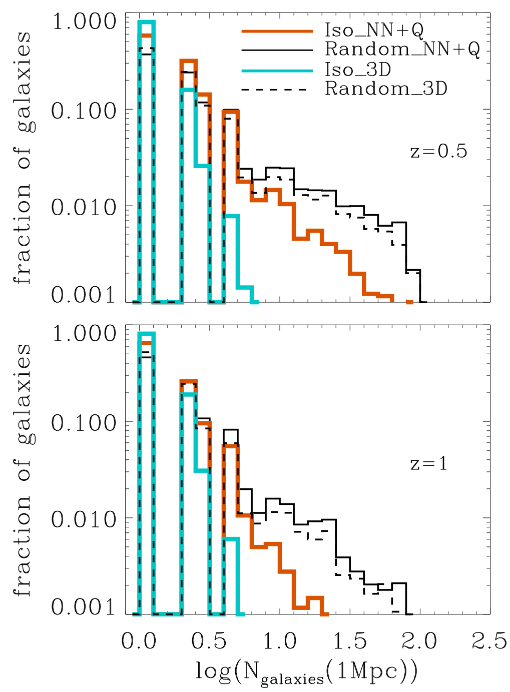

Figure 11. Distributions showing the number of galaxies within a 1 Mpc sphere (including the central one) by using the full 3D-real space information for progenitors of the Iso_NN+Q (orange) and of the Iso_3D$_{\rm RS}$ (cyan) samples, and of their mass-matched random samples (black). Different panels refer to different redshifts (top: z=0.5, bottom: z=1).

the random galaxies) with more than 3 galaxies within the 1 Mpc sphere is due to the satellite galaxies. Therefore, in a 2D-observationally selected galaxy sample, those that are 'misclassified' as isolated are largely the *satellite* galaxies, at least when considering our 3D$_{\rm RS}$ criterion.

The 'incompleteness' of the 2D_NN+Q galaxy sample, i.e. the fraction of 3D isolated galaxies that are not considered to be isolated due to projection effects, can be quantified by calculating the fraction of Iso_3D$_{\rm RS}$ galaxies which do not satisfy our 2D-observational criteria. We find that roughly 35 per cent of Iso_3D$_{\rm RS}$ do not satisfy the 2D-observational isolation criteria. The properties of the galaxies that are selected as isolated using our 3D criterion are, however, not significantly different from those that are selected as isolates using the 2D criterion. Therefore, projection effects reduce the completeness of isolated galaxy samples, but do not affect significantly the distributions of their physical properties.

5 ENVIRONMENTAL HISTORY OF PRESENT-DAY ISOLATED GALAXIES

As we have explained in section 1, the interest in isolated galaxies is driven by the fact that their physical properties are believed to be mainly determined by internal physical processes (i.e. by 'nature'). Isolated galaxies can thus be used as a reference sample for galaxies that are located in denser environments in order to disentangle the relative importance of nature and nurture in galaxy evolution. In this respect, it is important to understand to which extent isolated galaxies have been isolated during their entire life-time. In this section, we will study the 'environmental history of isolated galaxies'. In particular, we will analyse their parent halo mass distribution, and the number of neighbour galaxies within a sphere of 1 Mpc at different redshifts, and the redshift of the last major/minor merger events that isolated galaxies have experienced. We will focus on the Iso_NN+Q sample, the 3D-real space Iso_3D$_{\rm RS}$ sample, and the corresponding mass-matched random galaxy sets. For this analysis we only consider the *main progenitors* of the present-day isolated/random galaxies, i.e. the branch of the tree that is obtained by connecting the galaxy to its most massive progenitor at each node of the tree.

5.1 Halo masses

Fig. 10 shows the parent-halo mass distribution for the progenitors of present-day isolated galaxies (Iso_NN+Q: orange; Iso_3D$_{\rm RS}$: cyan) and of the corresponding mass-matched random samples (black lines), at $z = 0.5$ and 1. Independently of the galaxy sample considered, the high halo mass end is shifted towards lower halo masses (i.e. the number of galaxies in massive halos $M_{\rm halo} > 10^{13} M_{\odot}$ decreases) with increasing redshift. This is a natural consequence of hierarchical structure formation: small objects form first, and grow into larger structures via smooth accretion and merger events. At all redshifts, progenitors of the Iso_3D$_{\rm RS}$ sample contain a smaller number of galaxies residing in massive halos than the ones of the Iso_NN+Q sample.

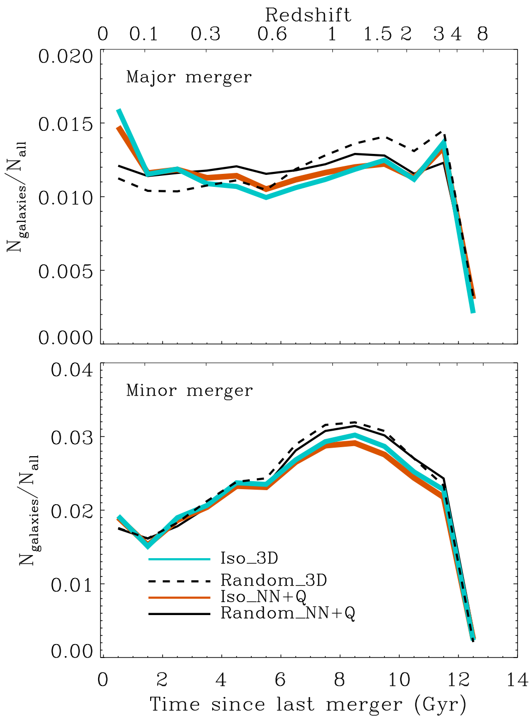

Figure 12. Distributions of the lookback time since the last major (mass-ratio of 1:1-1:4, top panel) and minor merger (mass-ratio of 1:4-1:10, bottom panel) event. Coloured lines are for isolated samples (Iso_NN+Q and Iso_3D$_{\rm RS}$), and black lines for the corresponding mass matched random samples.

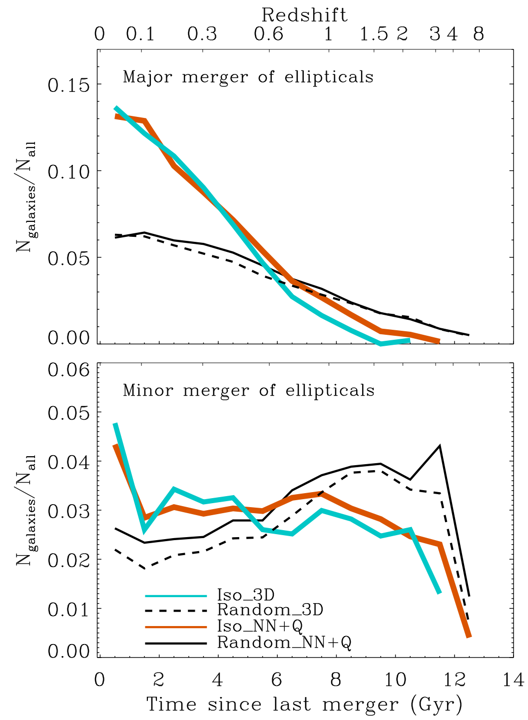

Figure 13. Same as Fig. 12, but now for isolated and randomly selected ellipticals with B/T>0.8. Coloured lines are for isolated ellipticals (Iso_NN+Q and Iso_3D$_{\rm RS}$), while black lines for the corresponding mass matched random samples.

Comparing the Iso_NN+Q or the Iso_3D$_{\rm RS}$ to the corresponding random galaxy samples, we find that the parent halo mass distribution is very close to that of isolated galaxies for low mass haloes ($M_{\rm halo} < 10^{13} M_{\odot}$). This is not surprising, given that these haloes dominate the halo mass function at all redshifts. If any, we find that a larger fraction of the progenitors of isolated galaxies is residing in low mass haloes with respect to progenitors of galaxies from the random sample (this is particularly evident for the Random_NN+Q). At the high mass end, there is a significantly larger fraction of progenitors of the random sample in massive halos with respect to progenitors of the isolated galaxy sample. Again, this difference is mainly caused by the larger amount of present-day satellite galaxies (which have been satellites for some time in the past) in the random sample than in the isolated sample.

5.2 Quantifying the degree of isolation since z=1

In this subsection, we ask the question whether present-day isolated galaxies have been isolated for a significant fraction of their life-time using the full 3D-real space information accessible in our models. Fig. 11 shows the distributions of the number of neighbour-galaxies within a co-moving 1 Mpc sphere for the progenitors of the 2D-isolated (Iso_NN+Q), the 3D-isolated (Iso_3D$_{\rm RS}$) and the corresponding mass-matched random samples at $z = 0.5$ and 1. Note that we have used the same definition of mass limits for neighbours at higher redshifts as at $z = 0$ and the 3D selection (i.e. mass limits vary with redshift as the stellar mass of the progenitor varies with redshift). Our neighbour samples include a small fraction of galaxies that are formally below the resolution limit of the simulation, but this does not affect the results discussed here.

We find that the amount of galaxies with a large number of neighbour galaxies within a 1 Mpc sphere slightly decreases with increasing redshift, independently of the galaxy sample considered. For the Iso_NN+Q sample, about 60 per cent of present-day isolated galaxies had no other neighbour galaxy within a 1 Mpc sphere at z=0.5. The fraction slightly increases to about 65 per cent at z=1. The same fractions for the Iso_3D$_{\rm RS}$ sample, are larger than for the Iso_NN+Q sample: at any redshift (since z=1), roughly 80 per cent of present-day isolated galaxies have been isolated according to our 3D criterion. Therefore, Iso_3D$_{\rm RS}$ galaxies have been on average 'more isolated' during their life than Iso_NN+Q galaxies. This is not surprising as already at z=0 only 56 per cent of Iso_NN+Q satisfy the 3D-real space isolation criterion (see Fig. 9). Considering only the subsample of present-day elliptical isolated galaxies ($B/T > 0.8$), we find that at $z \sim 0.5$ a smaller fraction of progenitors of present-day early-type galaxies ($\sim$ 45 per cent in the Iso_NN+Q, and $\sim$ 75 per cent in the Iso_3D$_{\rm RS}$ sample) have been isolated. At higher redshift, there is no significant difference between the isolation degree of progenitors of isolated early-types and all isolated galaxies. This indicates that isolated ellipticals have likely experienced their merger events at $z < 0.5$. We will discuss this in more detail in the following section.

In conclusion, following the progenitors of 2D isolated

galaxies, we find that a slightly larger fraction of them can be classified as isolated (or had only few neighbours) in the past (at $z = 0.5, 1$) than today. However, we note that we are using co-moving spheres of 1 Mpc, which corresponds to spheres of ~ 660 and ~ 500 kpc in physical units at $z = 0.5$ and $z = 1$, respectively, what may explain the slightly higher fractions of isolated progenitors in the past. As a further consequence, a fixed number of neighbours also corresponds to a higher probability of interactions at higher redshift (where galaxies are on average closer). The bottom panel of Fig. 11 shows that at $z = 1$, only a small fraction of ~ 7 per cent of the progenitors of 2D isolated galaxies have had more than 3 neighbours within a co-moving radius of 1 Mpc, which corresponds to a poor galaxy cluster.

5.3 Minor and major mergers of isolated galaxies

In order to investigate in more detail the past degree of isolation for galaxies selected as isolated at $z = 0$, we follow back in time the main progenitor of each isolated galaxy, and record the time corresponding to the last merger (only mass-ratios above 1:10). We distinguish between major (mass-ratio of 1:1-1:4) and minor mergers (mass-ratio of 1:4-1:10). We find that roughly 45 per cent of the present-day isolated galaxies (Iso_NN+Q and Iso_3D$_{\rm RS}$ samples) have had at least one merger event during their entire life, and one third of these merging galaxies experienced at least one major merger. This shows that minor mergers provide a larger contribution to the overall stellar mass assembly than major mergers, consistent with earlier studies (e.g. Guo & White 2008). Among the 2D isolated galaxies that experienced at least one merger, we find that about 24 per cent experienced more than one mergers, but none had more than four. I.e. the majority (about 76 per cent) of these galaxies experienced at most only one merger event during their lifetime, and in most of the cases this was a minor merger. This result is nearly independent of the isolated galaxy sample considered (21 per cent of the 3D isolated galaxies with more than one merger), and it is also true for the corresponding mass-matched random samples (25 per cent and 23 per cent for the 2D and 3D mass-matched random samples, respectively). Therefore on average, isolated galaxies have undergone *roughly the same amount* of merger events in their life as a 'typical' galaxy of *similar stellar mass*. This implies that the isolation degree of galaxies of a given stellar mass has no significant influence on the merging history of their progenitor galaxies.

Fig. 12 illustrates the distribution of the lookback times since the *last major or minor merger event* (top and bottom panel, respectively). We find that about 5 per cent of present-day isolated and mass-matched random galaxies had their last major or minor merger during the last Gyr. Turning to only major mergers, the time distributions hardly change for the different galaxy samples, and since z=3 they are nearly flat for all galaxy samples. On average, isolated and randomly selected galaxies have had their last major merger event roughly 6 Gyr ago. In contrast, for minor mergers, the time distributions are peaking at $z \sim 1$ and the amount of galaxies having had a minor merger at $z < 1$ decreases with decreasing time, again independently of the considered galaxy sample. Our results are consistent with the study by Guo & White (2008), that is based on the same model used in this study.

Considering the subsample of isolated ellipticals (with $B/T > 0.8$), they exhibit a very different behaviour compared to randomly selected ellipticals or average isolated galaxies. Fig. 13 shows the distributions of the lookback times since the last major or minor merger event of Iso_NN+Q and Iso_3D$_{\rm RS}$ *elliptical* galaxies and the corresponding mass-matched random ones. For major mergers (top panel of Fig. 13), the time distributions for isolated ellipticals are skewed towards decreasing lookback times. Randomly selected ellipticals show a similar but weaker trend. On average, isolated early-types experienced their last major merger event roughly 3 Gyr ago, much later than randomly selected ellipticals (5 Gyr) and than 'average' isolated galaxies. A similar trend is visible for minor mergers (bottom panel of Fig. 13). If the last major merger event is responsible for the formation of the bulge, then our results suggest that the bulge masses of isolated ellipticals have been assembled on average only 3 Gyr ago. In contrast, bulges of randomly selected early-type galaxies of the same mass have been assembled on average significantly earlier (5 Gyr ago).

6 SUMMARY AND CONCLUSION

In this work we have presented a detailed, statistical study of isolated galaxies extracted from publicly available galaxy catalogues based on the merger trees extracted from the Millennium simulation (De Lucia & Blaizot 2007). We have focused on basic, present-day properties of model isolated galaxies considering different selection criteria and based on the same parent galaxy sample ($m_{\rm b,j} < 15.7$). For our analysis, we have used 2D criteria widely adopted in the observational literature (Verley et al. 2007, AMIGA sample), as well as a more stringent 3D selection criterion, where we take advantage of the full 3D-real space information available in simulations. Our main results can be summarised as follows:

(i) 2D selected isolated galaxies have relatively low stellar masses ($< 10^{11.5} M_\odot$) and a significantly high fraction of central galaxies, with respect to galaxies residing in high-density regions. Compared to randomly selected sample of galaxies with the same mass distribution, isolated galaxy samples are characterised by a larger fraction of late-type star forming galaxies, tend to reside in lower mass haloes ($M_{\rm halo} \leqslant 10^{13} M_\odot$), and contain slightly less massive black holes. We find that all 2D samples include a small fraction of satellite galaxies, most of which reside at the outskirts of their parent dark matter haloes, where the galaxy number density is lower.

Therefore, the observational criteria that are commonly used to define isolated galaxy samples, are effective in selecting samples of galaxies whose physical properties are in qualitative agreement with observational measurements, at least in terms of relative trends with respect to the global galaxy population. However, these samples are 'contaminated' by a fraction of satellite galaxies, whose physical properties are influenced by environmental physical processes, that ranges between 10 and 15 per cent.

(ii) When comparing different 2D-selection criteria (based on cuts in the tidal strength parameter Q and/or in the

local galaxy number density Σ_{5NN}), we find that the tidal strength parameter represents a stronger constraint for isolation, as it excludes small dense systems like pairs or triplets. This clearly shows that adding the mass information is important for selecting isolated galaxies.

Our 3D isolated criterion is based on the same parent sample used for the 2D selection, but assumes that galaxies are isolated if they have no neighbour within a sphere of 1 Mpc centred on the isolated candidate with stellar mass down to one order of magnitude below that of the isolated candidate. Adopting these (somewhat arbitrary) definitions, we find that roughly two thirds of the 2D isolated galaxies are also completely isolated when using the 3D criterion, and that most of the 'misclassified' 2D isolated galaxies are satellite galaxies. We also show that the 2D sample is 'incomplete' as roughly one third of 3D selected isolated galaxies are not included in the 2D sample. In particular, we find that our 2D selected samples are significantly 'contaminated' at a level of about 18 per cent, and 'complete' at a level of 65 per cent.

(iii) Our 2D isolated samples contain a very small fraction (about $3-4$ per cent) of bulge dominated galaxies (bulge-to-total ratio of $B/T > 0.8$). We find that the bulges of these galaxies have been build mainly through merger events, two thirds of which are classified as minor mergers (mass ratio between 1:4 and 1:10). The mergers determining the assembly of these bulges take place relatively late (about 3 Gyr ago), later than the last major merger of a 'typical' elliptical galaxy that is not classified as isolated (about 5 Gyr ago).

Independently of the isolated galaxy sample, about 45 per cent of the galaxies experienced at least one merger event but only about 24 per cent of them have had more than one merger events and none experienced more than four mergers. Most of the mergers (about two thirds) are minor. Almost the same fractions are found for a randomly selected sample of galaxies that has the same mass distribution of the isolated samples. Therefore, the 'isolation' of galaxies of given stellar mass does not influence significantly their merger history. Thus, we want to point out that the differences in the galaxy properties between the isolated and the corresponding mass-matched random samples are hardly caused by a difference in their merger histories, but mainly by the larger fraction of satellites in the random samples, as satellites can experience environmental processes.

(iv) Using the merger trees available from the simulated catalogues, we have studied the degree of isolation of our 2D isolated galaxies in the past. Our results show that progenitors of isolated galaxies have preferentially resided in 'underdense' regions, compared to those of random galaxies. Nevertheless, a significant fraction of the galaxies classified as isolated at $z = 0$ (35-40 per cent for the 2D samples) have not been'isolated' since $z = 1$ when considering our 3D-real space criterion. I.e. following the main progenitors of 2D isolated galaxies, we find that a significant fraction of them have neighbours within a comoving sphere of 1 Mpc radius, but only 7 per cent have more than 3 neighbours at $z = 1$. We note that this radius corresponds to an increasingly smaller physical radius at higher redshift. So a fixed number of neighbours corresponds to an increasing probability of interactions at increasing redshift. However, we stress that the majority of the galaxies classified as isolated (about 88 per cent) have experienced at most one minor merger event during their life-time, and this merger occurred on average when the Universe was half its present age. Therefore, nurture does not play a relevant role in the evolution of these galaxies, and the approximation that these galaxies have experienced only internal physical processes appears to be valid.

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